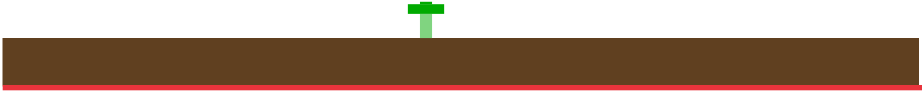
Multi-GNSS aspects in global and regional solutions

Rolf Dach and the CODE AC team

Astronomical Institute, University of Bern, Switzerland

ISSI Forum on
GNSS for Monitoring Earth Deformation
(March 16-18, 2026, Bern)

Assumptions in GNSS data processing



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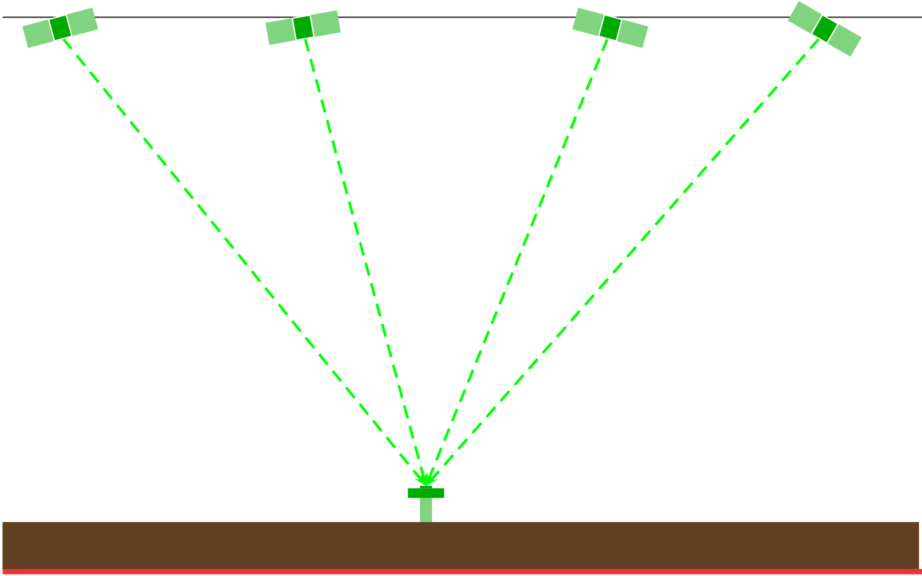

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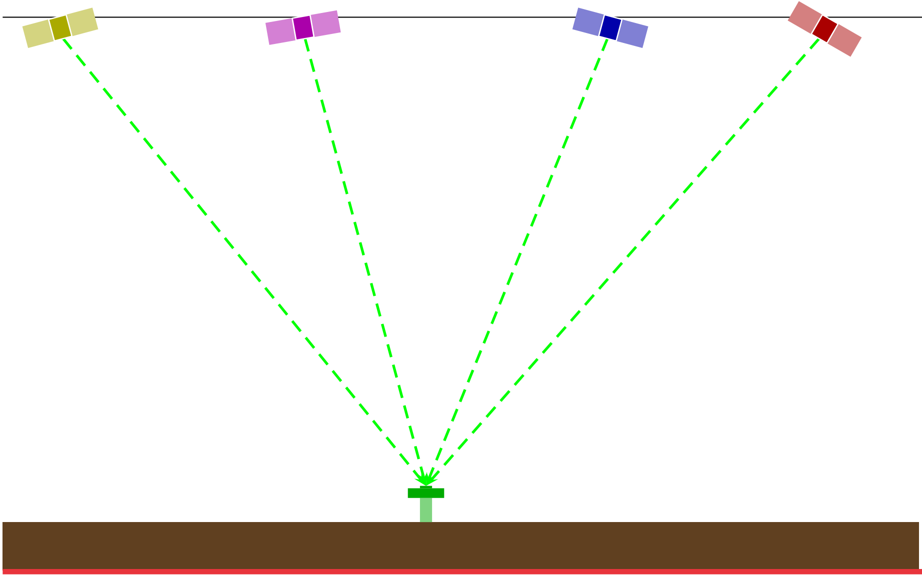

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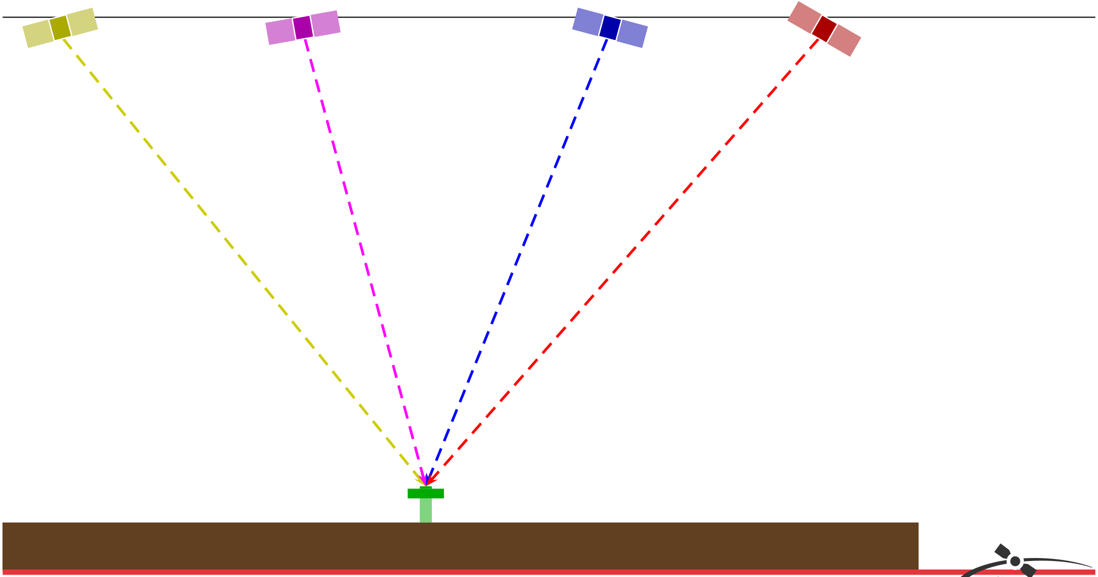

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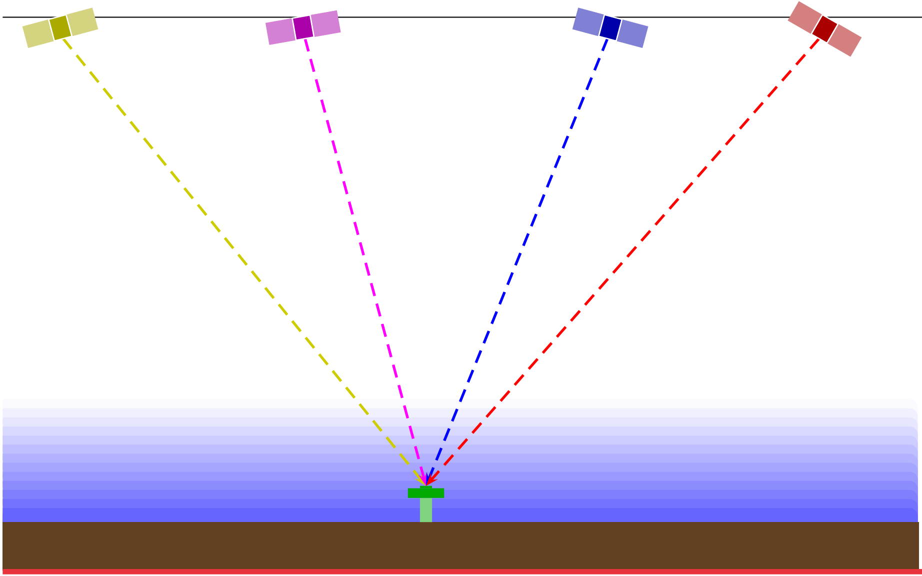

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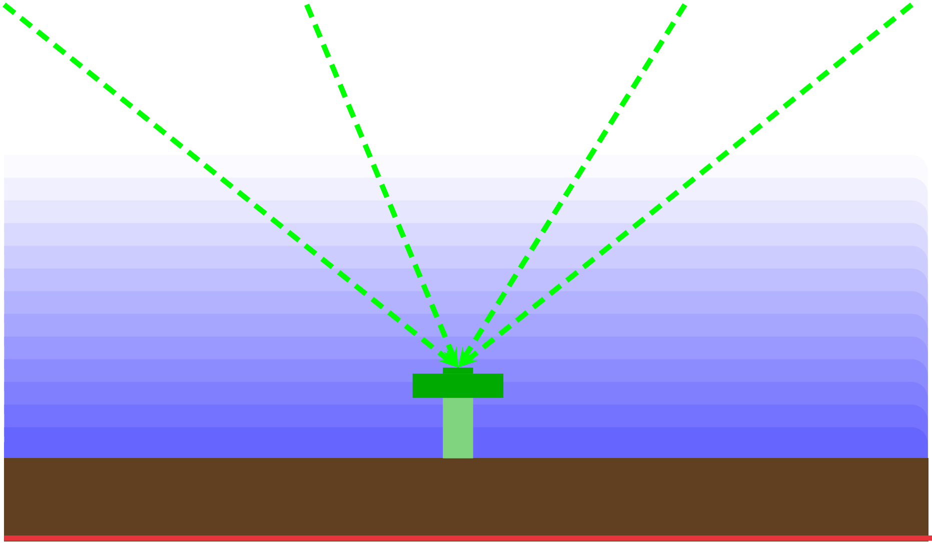

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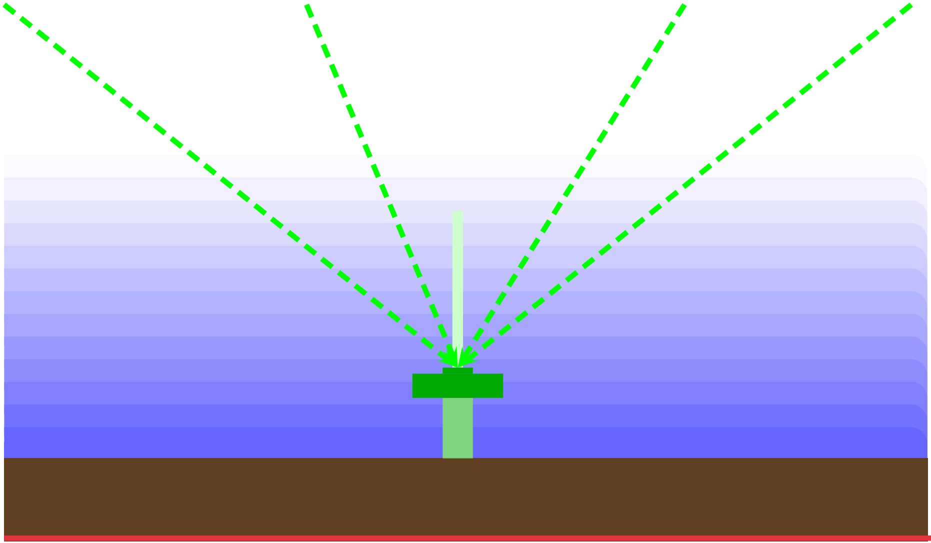

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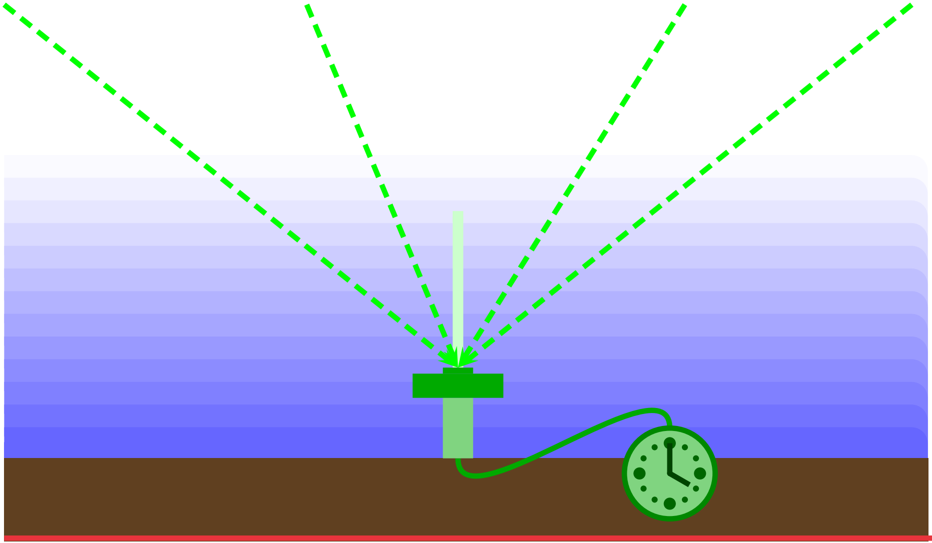

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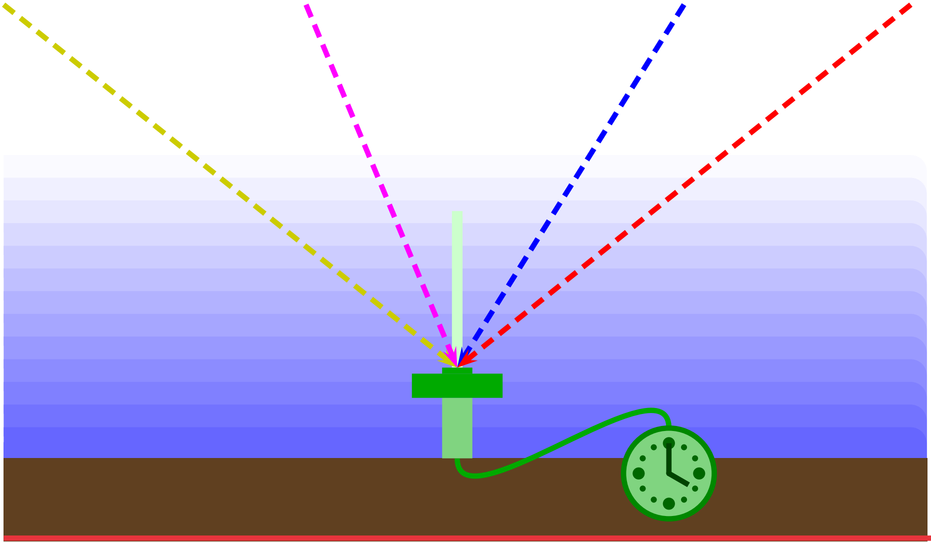

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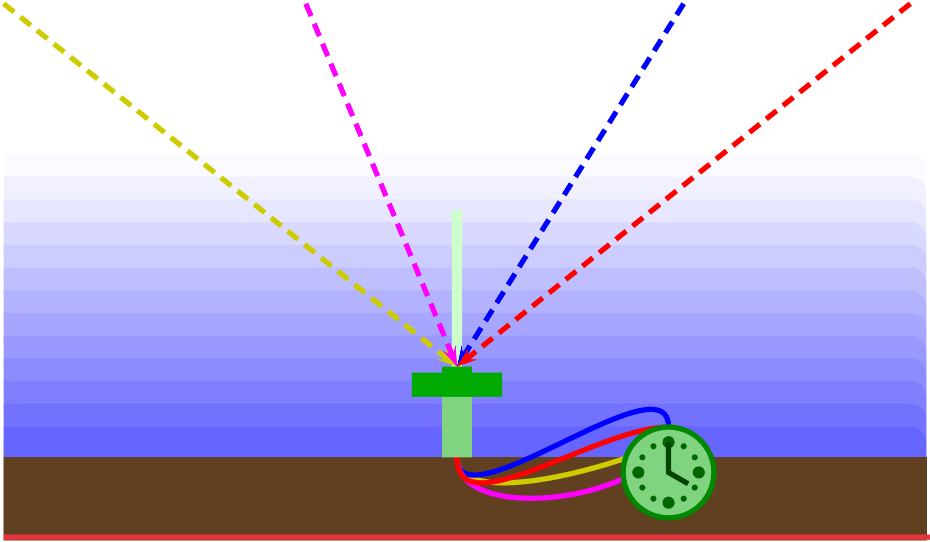

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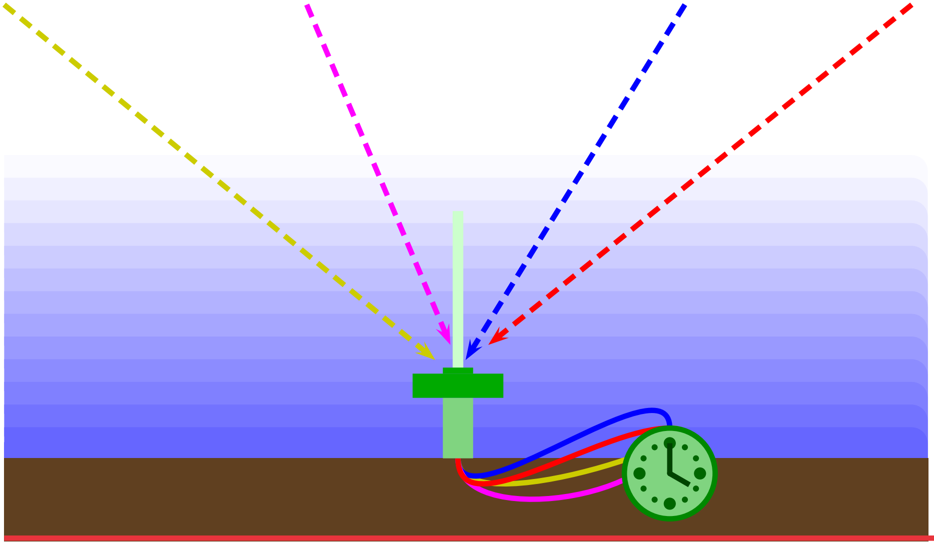

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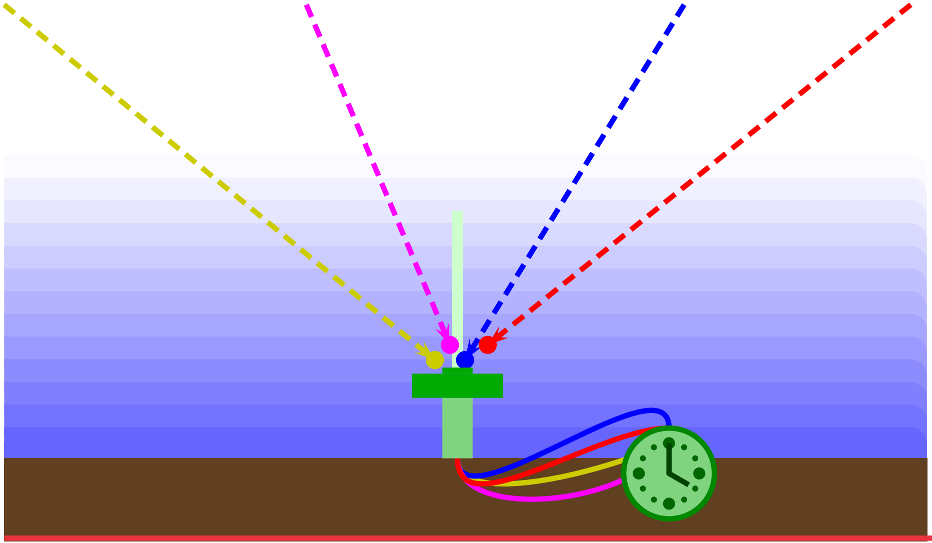

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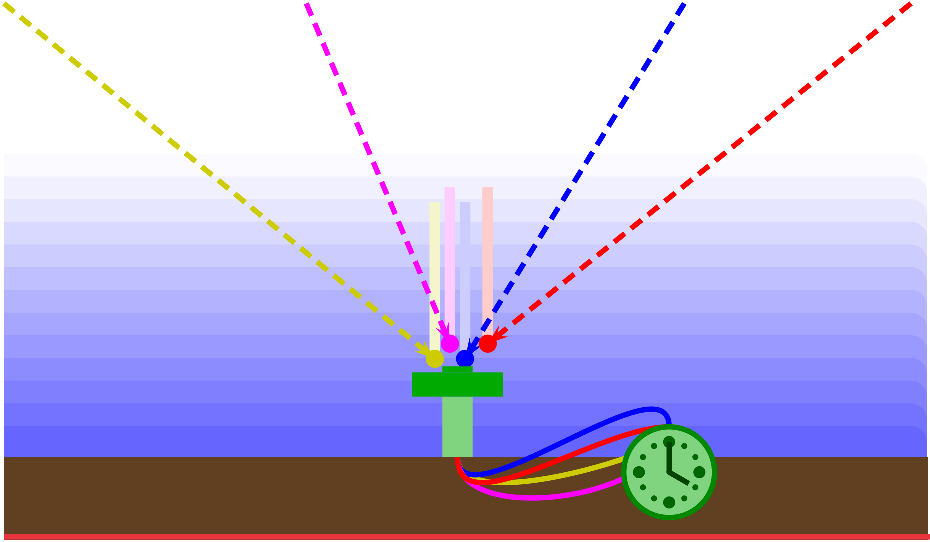

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- This applies even, if the signals come from different GNSS.
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  - Antenna phase center offsets are perfectly calibrated across the systems.
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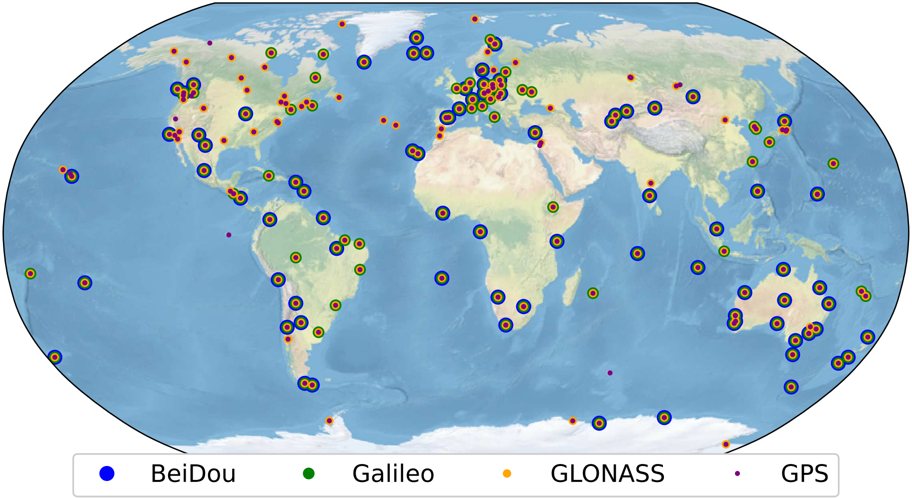
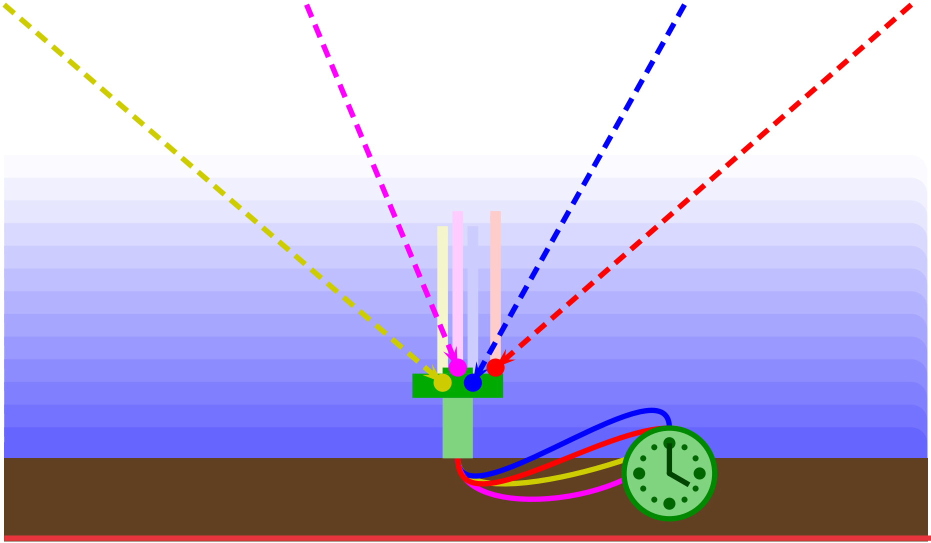
  - No deficiency in antenna phase center variations does map into troposphere model.

- There is only a constant hardware delays in the receiver
  - across various frequencies (in particular GLONASS) and
  - independent from the different signals from the various GNSS.

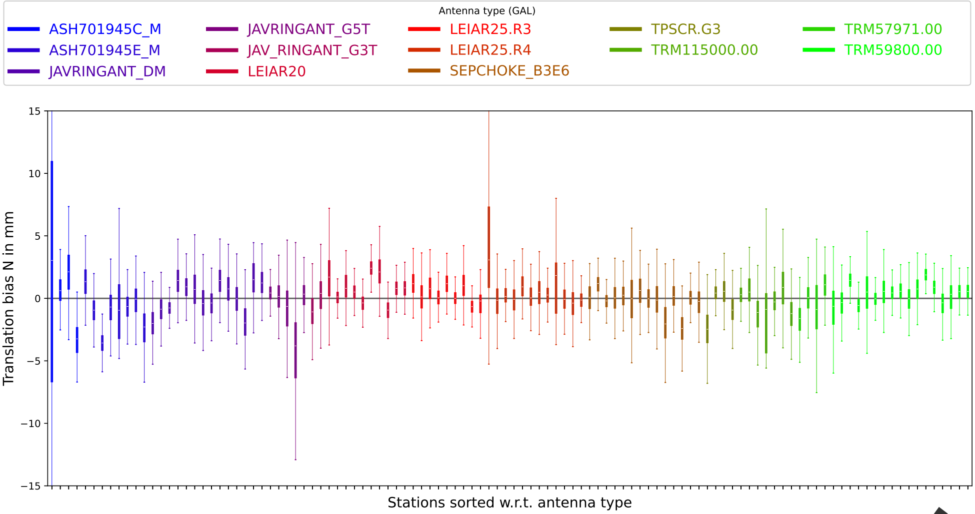
Network from CODE final solution



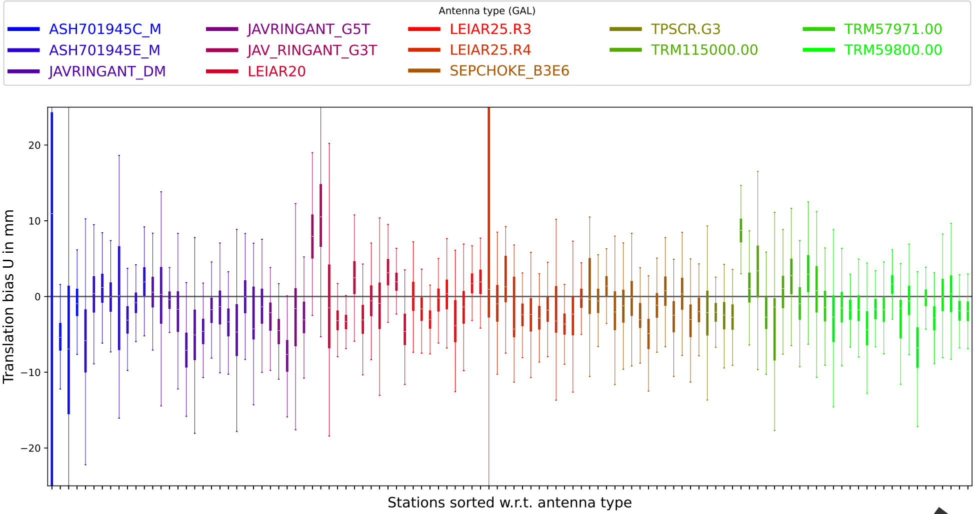
Experimental setup to proof these assumptions



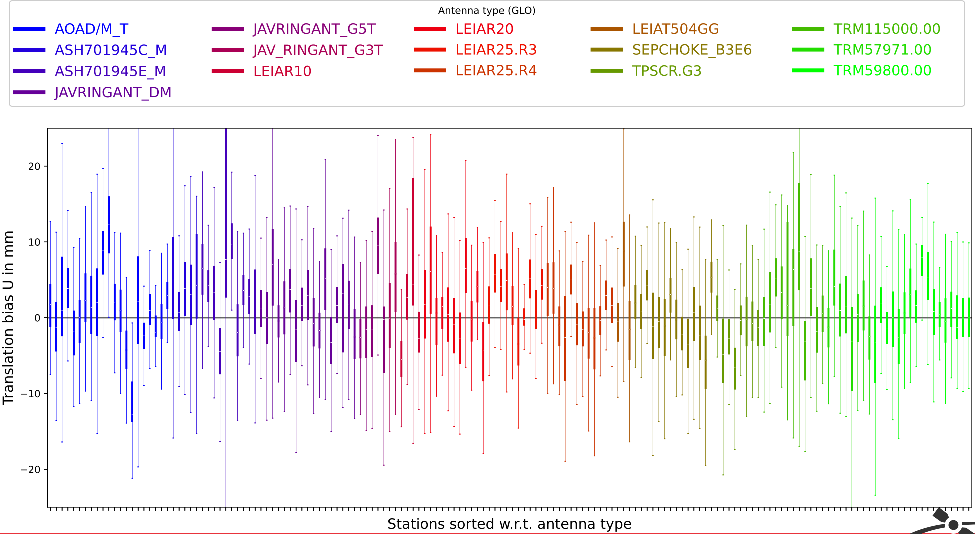
Station coordinates: translation biases (Galileo, north)



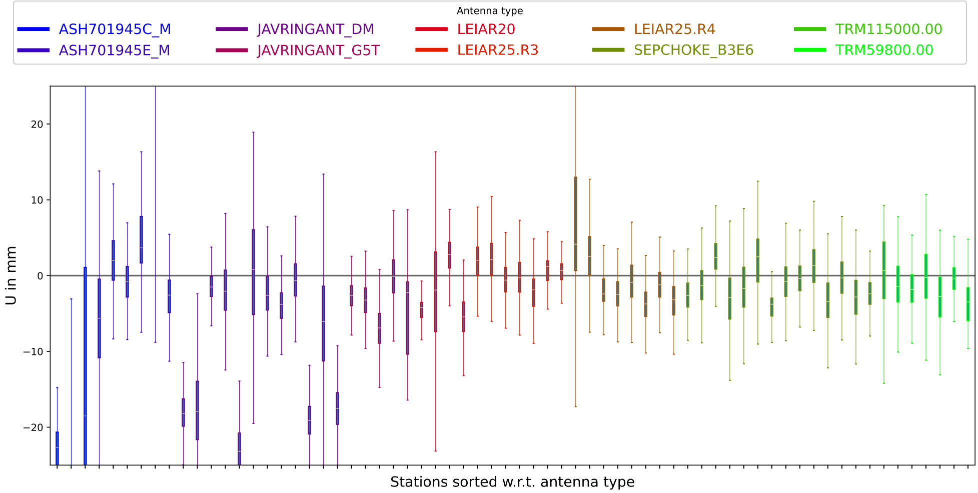
Station coordinates: translation biases (Galileo, vertical)



Station coordinates: translation biases (GLONASS, vert.)



Station coordinates: translation biases (BeiDou, vertical)



Conclusion for GNSS-based deformation studies

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- GNSS receiver antenna calibrations are typically limited by the uncertainty of the calibration process.
  - Use only antennas for systems and frequencies where they are designed for.
  - Use only antennas with proper calibrations.

Conclusion for GNSS-based deformation studies

- Real crustal deformations are visible in all GNSS solutions.
- GNSS receiver antenna calibrations are typically limited by the uncertainty of the calibration process.
  - Use only antennas for systems and frequencies where they are designed for.
  - Use only antennas with proper calibrations.
  - When changing an antenna at a marker, changes in the station coordinates are expected.
- When ever possible, don't change the equipment.
  (apply in particular for antennas but also for receivers and in some cases even for firmware)

Conclusion for GNSS-based deformation studies

- Real crustal deformations are visible in all GNSS solutions.

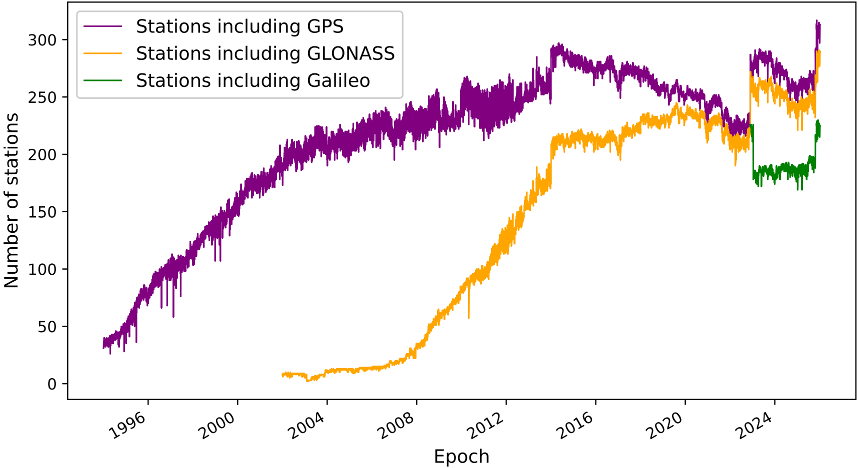
- Frequencies used by various GNSS (without GLONASS):

	1.57 GHz	1.23 GHz	1.12 GHz
GPS:	L1	L2	L5
Galileo:	E1		E5a
BeiDou:	B1A/C		B2a
QZSS:	L1	L2	L5

Frequencies/signals as currently used by the IGS.

- In particular GPS-based results should be confirmed by another systems.

CODE GNSS Processing



Development of the number of tracking stations in the CODE final processing

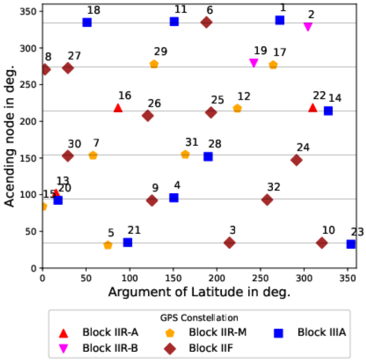
Constellation in numbers

Orbit elements for GPS satellites

a: 26 560 km

e: 0 (circular orbit)

i: 55°



Status: 12-Mar-2026

Constellation in numbers

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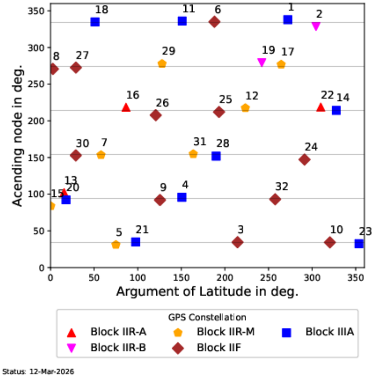
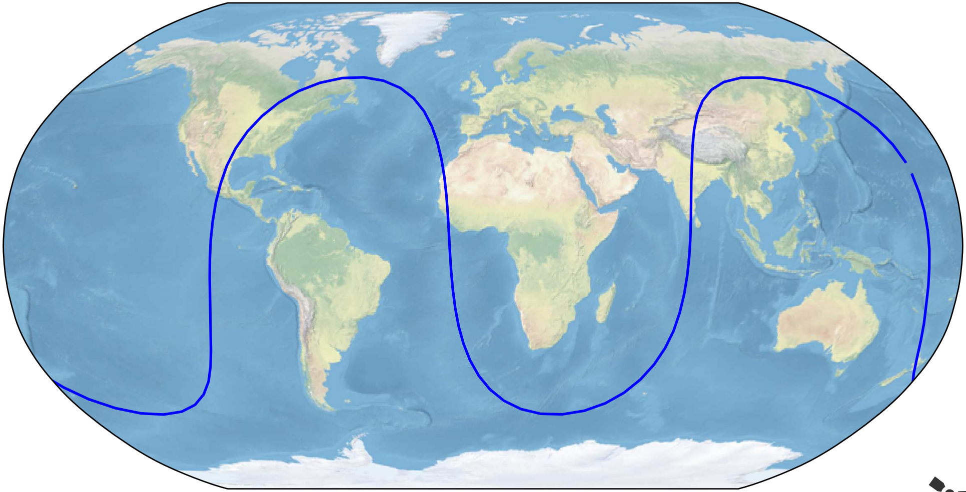


Repetition rates

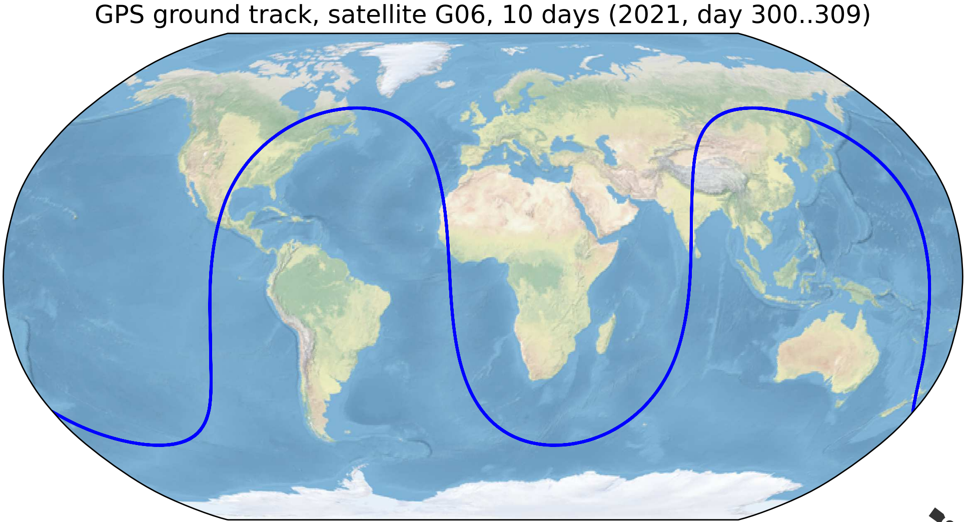
revolution period	11 h 58 min	
constellation	1 sidereal day	
geometry	23 h 56 min	1 sidereal day

GPS constellation

GPS ground track, satellite G06, 1 day (2021, day 300)



GPS constellation



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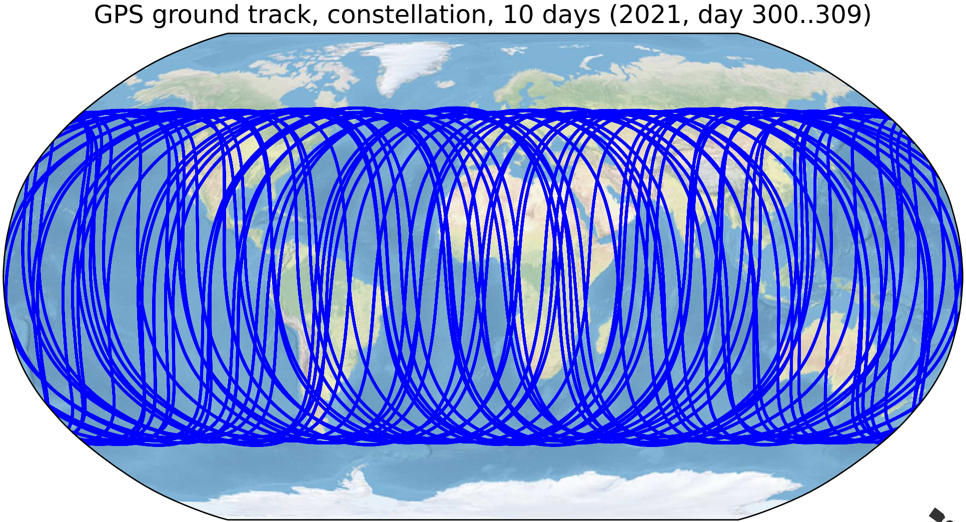


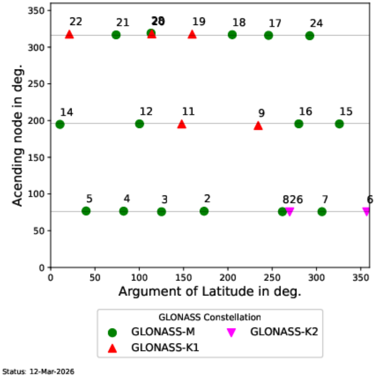
Constellation in numbers

Orbit elements for GLONASS satellites

a: 25 510 km

e: 0 (circular orbit)

i: 64.8°



GLONASS constellation

Constellation in numbers

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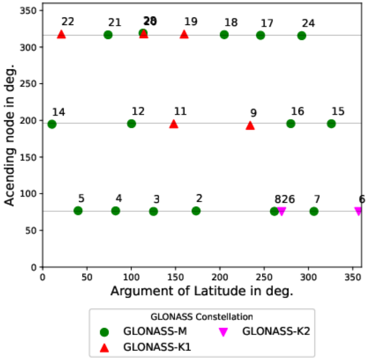


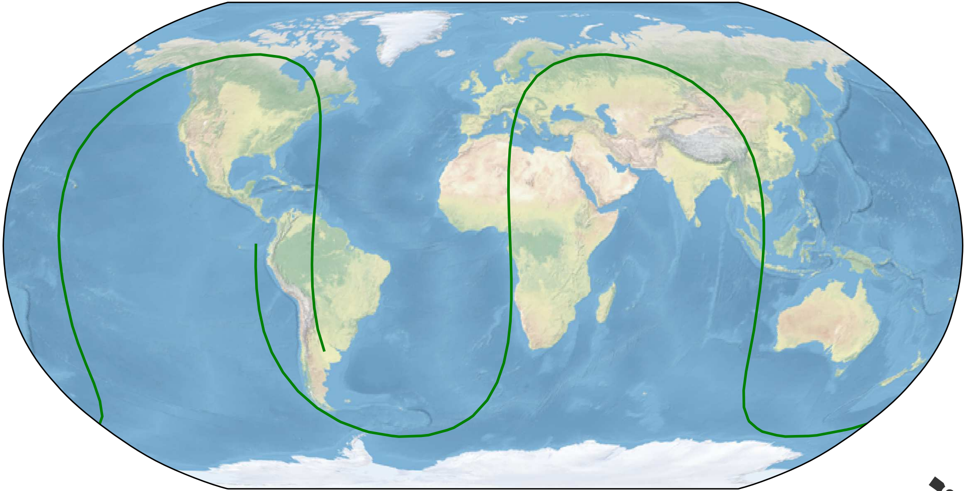
Status: 12-Mar-2026

Repetition rates

revolution period	11 h 16 min	
constellation	8 sidereal day	
geometry	$\frac{1}{3}$ sidereal day	satellite in the next orbital plane
	1 sidereal day	satellite in the same orbital plane

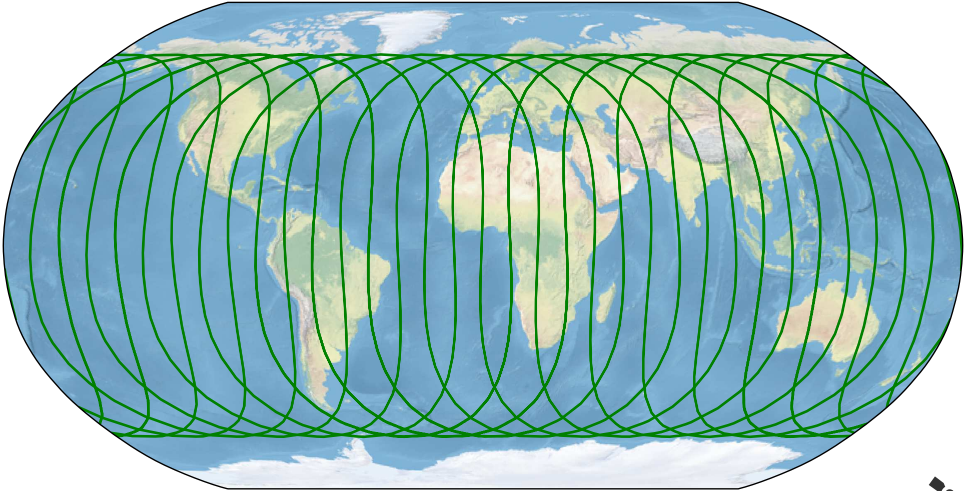
GLONASS constellation

GLONASS ground track, satellite R08, 1 day (2021, day 300)



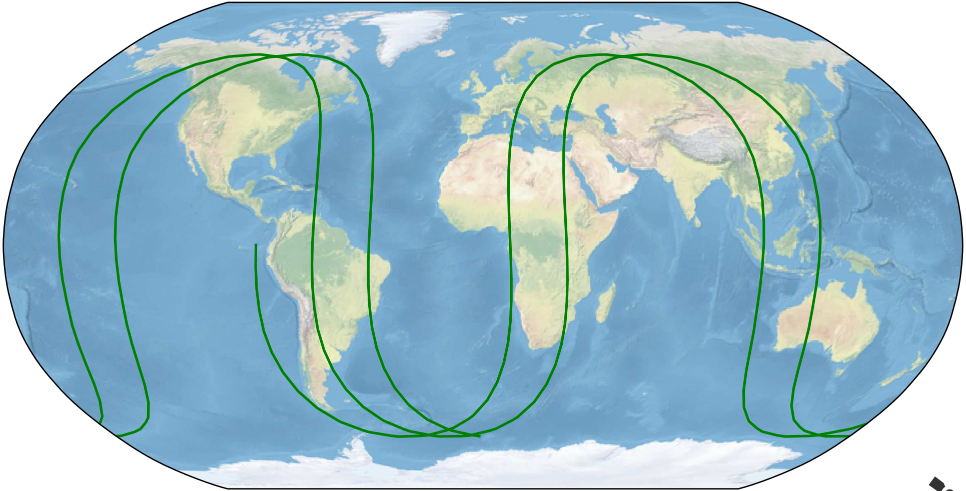
GLONASS constellation

GLONASS ground track, satellite R08, 10 days (2021, day 300..309)



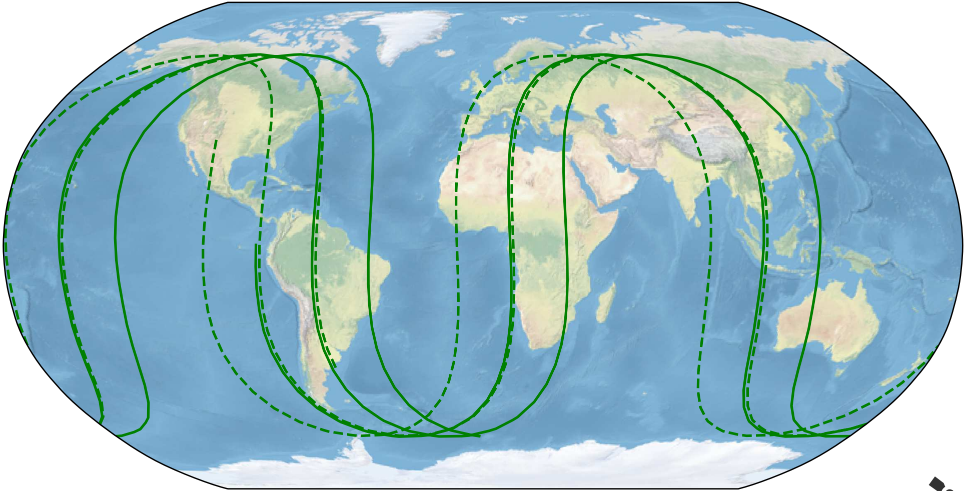
GLONASS constellation

GLONASS ground track, satellite R08, 2 days (2021, day 300..301)



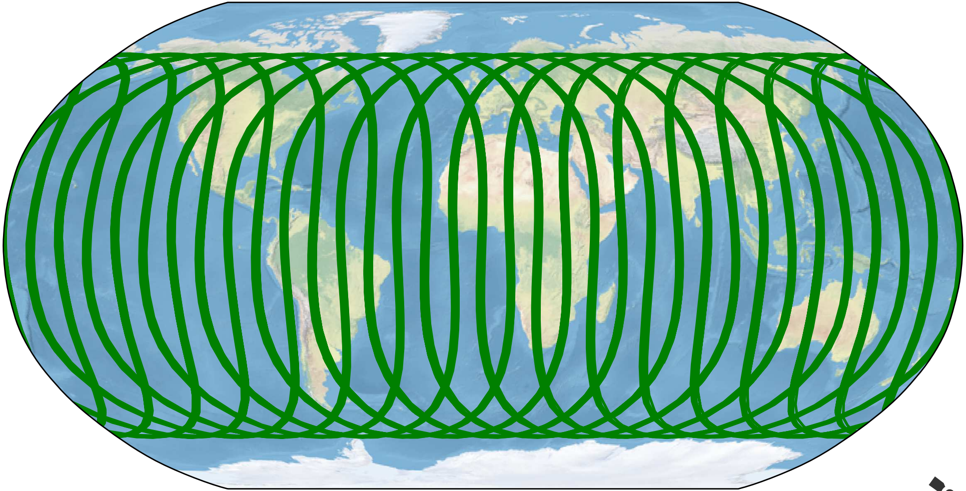
GLONASS constellation

GLONASS ground track, satellite R08&R01, 2 days (2021, day 300..301)



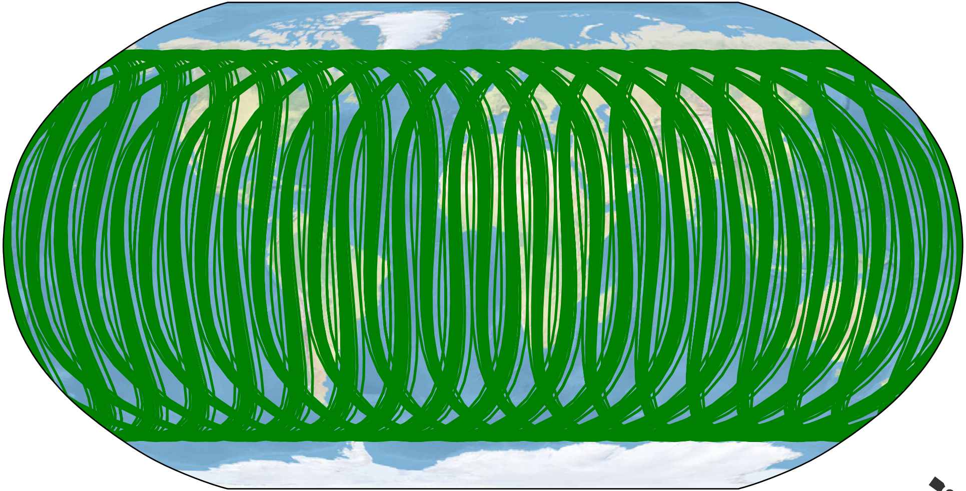
GLONASS constellation

GLONASS ground track, one plane, 10 days (2021, day 300..309)



GLONASS constellation

GLONASS ground track, constellation, 10 days (2021, day 300..309)



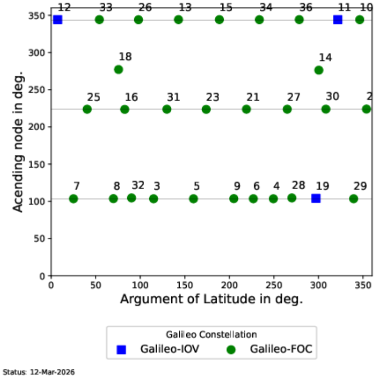
Constellation in numbers

Orbit elements for Galileo satellites

a: 30 000 km

e: 0 (circular orbit)

i: 56°



Galileo constellation

Constellation in numbers

Orbit elements for Galileo satellites

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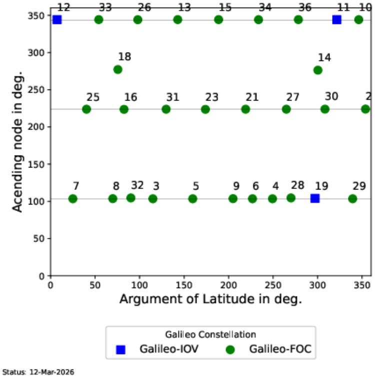
e:	0	(circular orbit)
i:	56°	

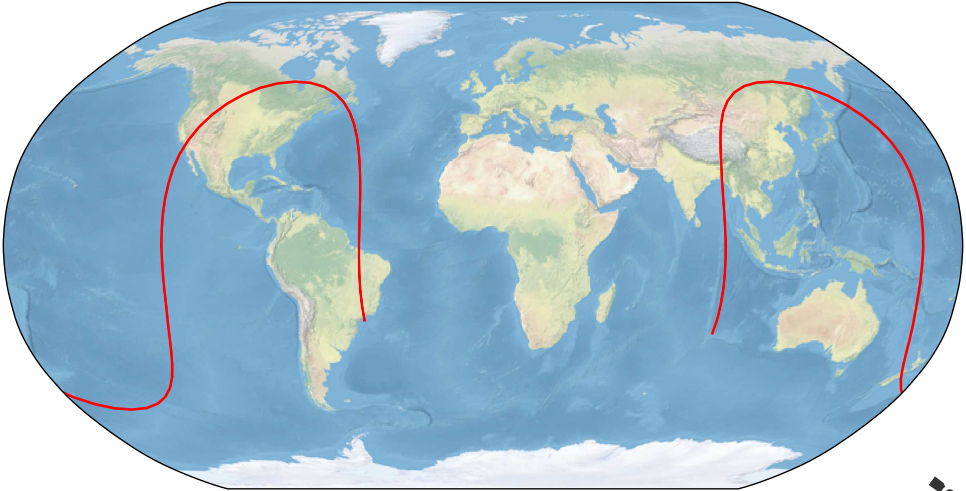


Repetition rates

revolution period	13 h 45 min	
constellation	10 sidereal day	
geometry	$\frac{10}{3}$ sidereal day	satellite in the next orbital plane
	10 sidereal day	satellite in the same orbital plane

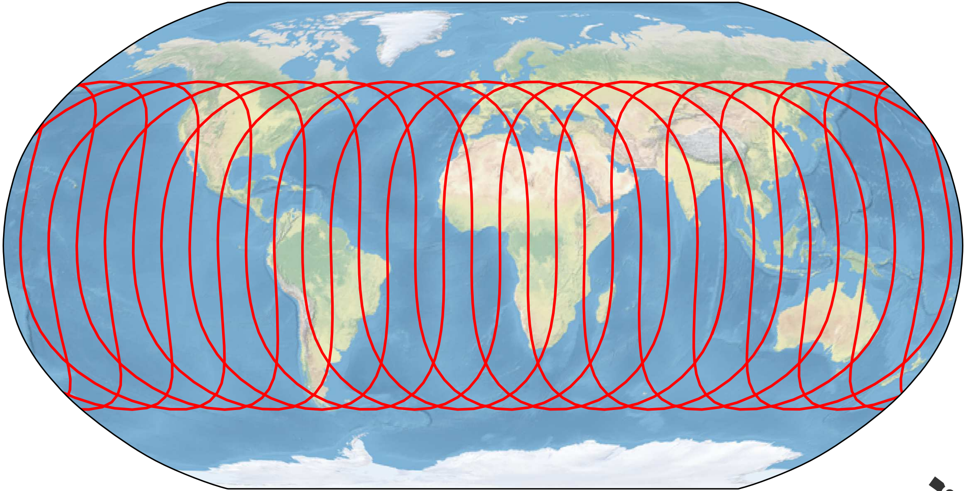
Galileo constellation

Galileo ground track, satellite E05, 1 day (2021, day 300)



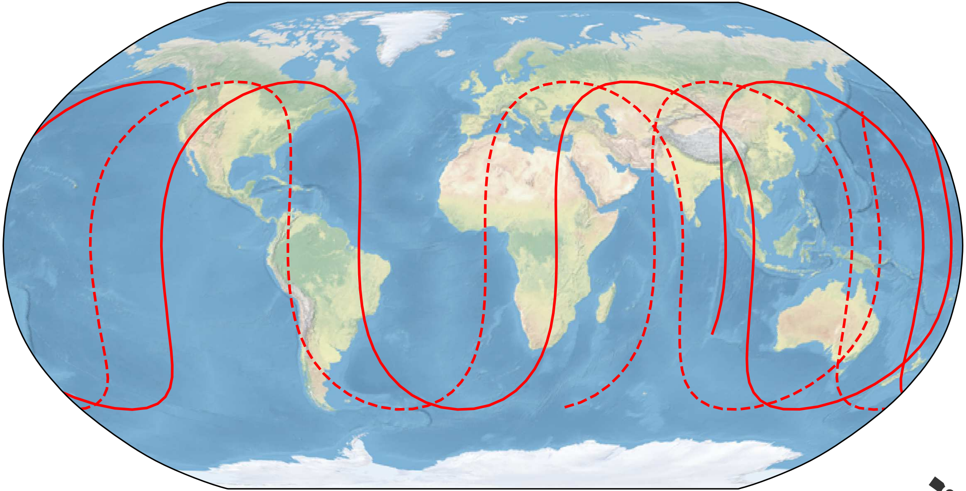
Galileo constellation

Galileo ground track, satellite E05, 10 days (2021, day 300..309)



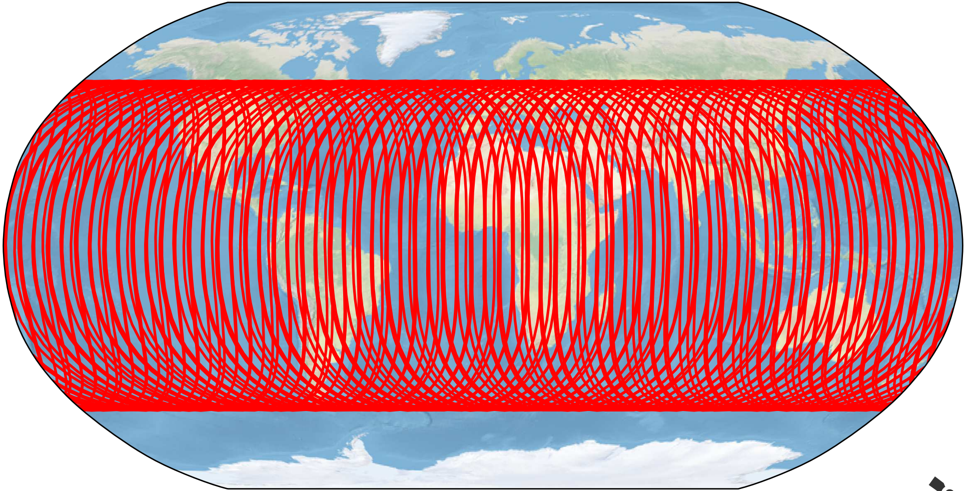
Galileo constellation

Galileo ground track, satellite E05&E03, 2 days (2021, day 300..301)

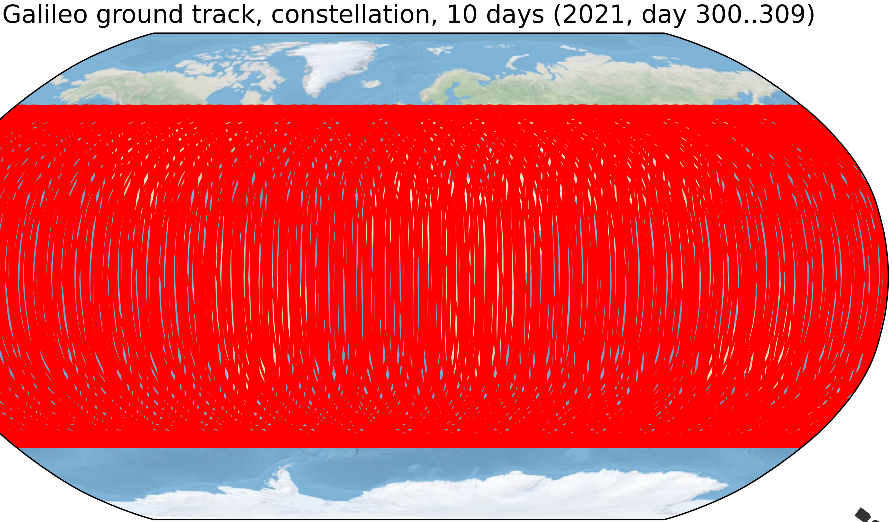


Galileo constellation

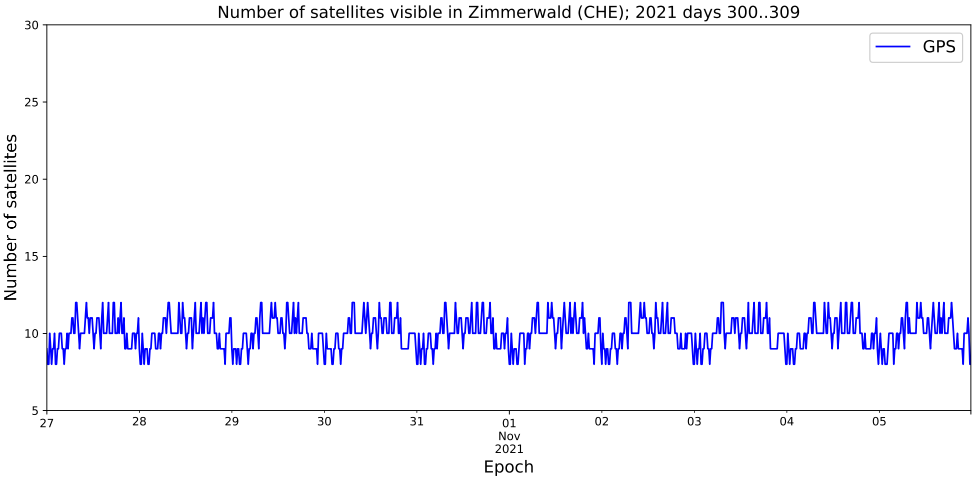
Galileo ground track, one plane, 10 days (2021, day 300..309)



Galileo constellation



Number of visible satellites



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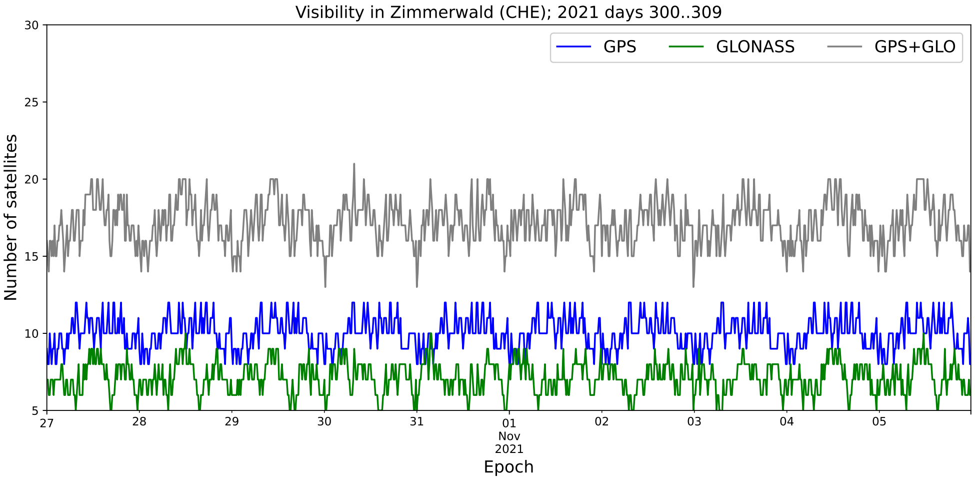

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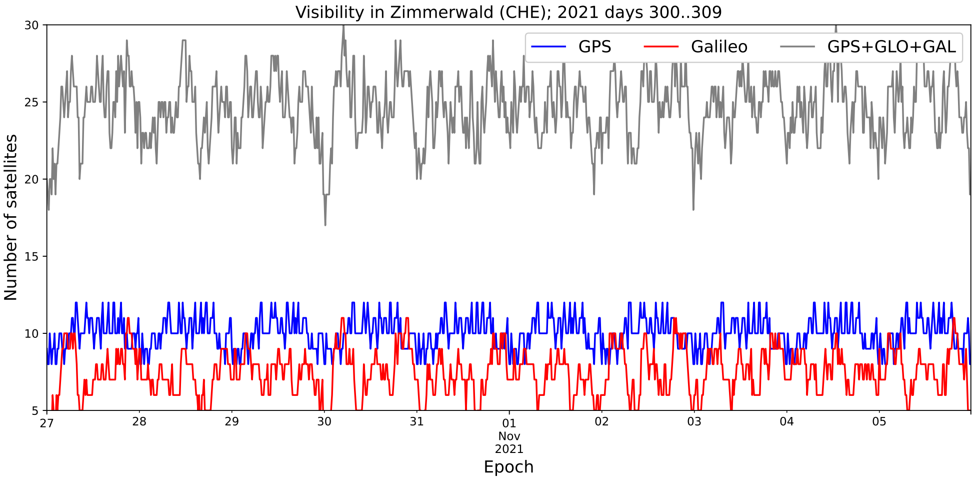
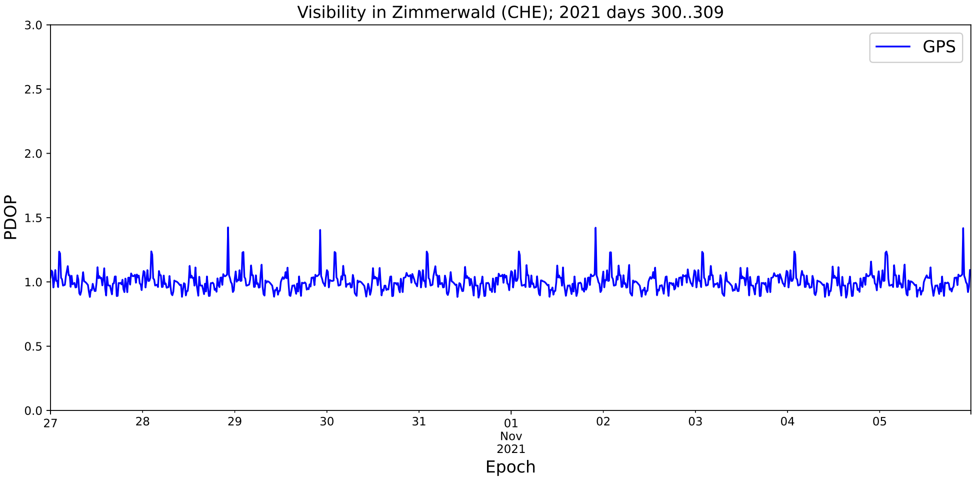


PDOP: measuring the satellite geometry



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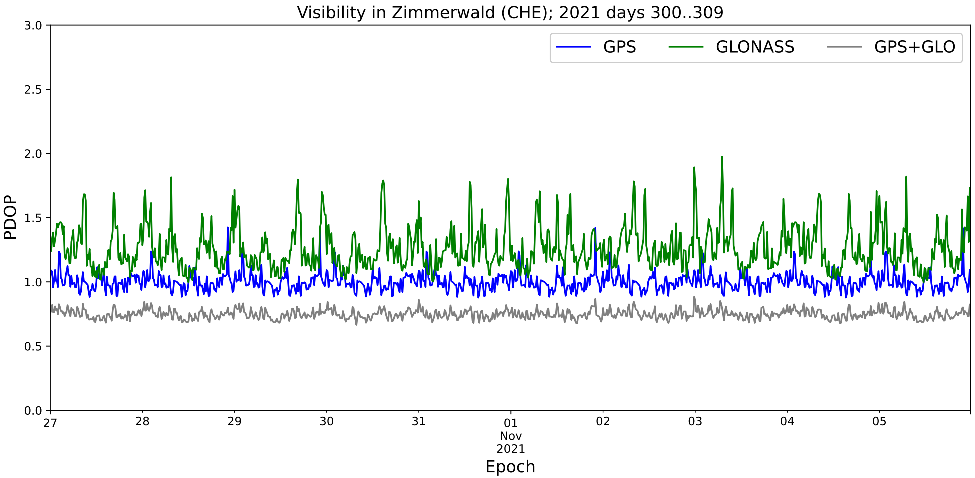

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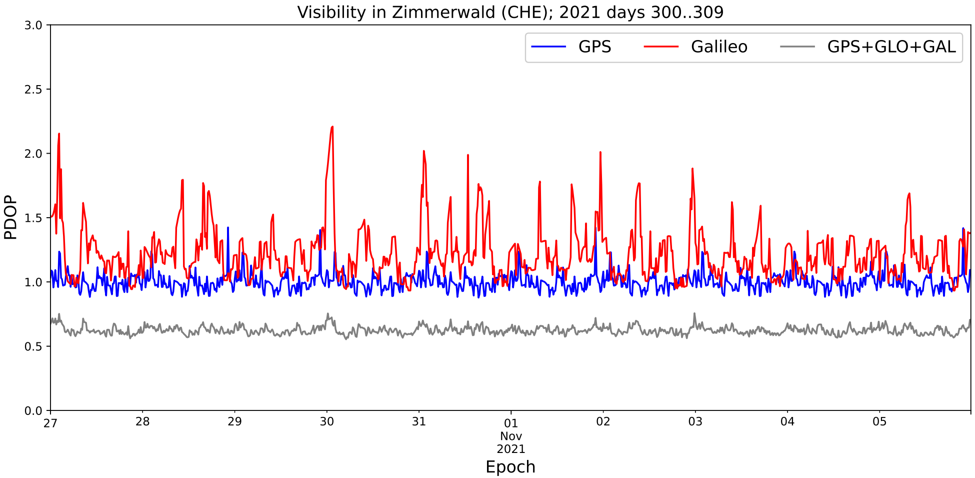

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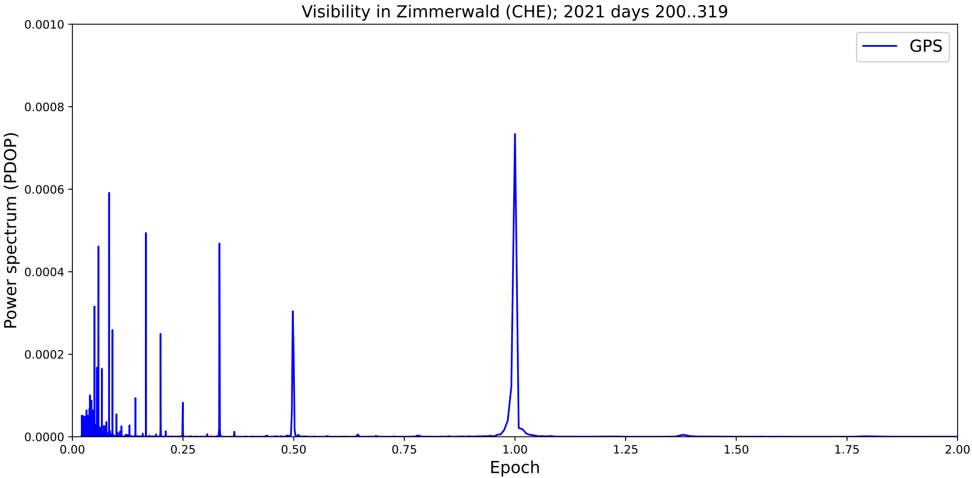

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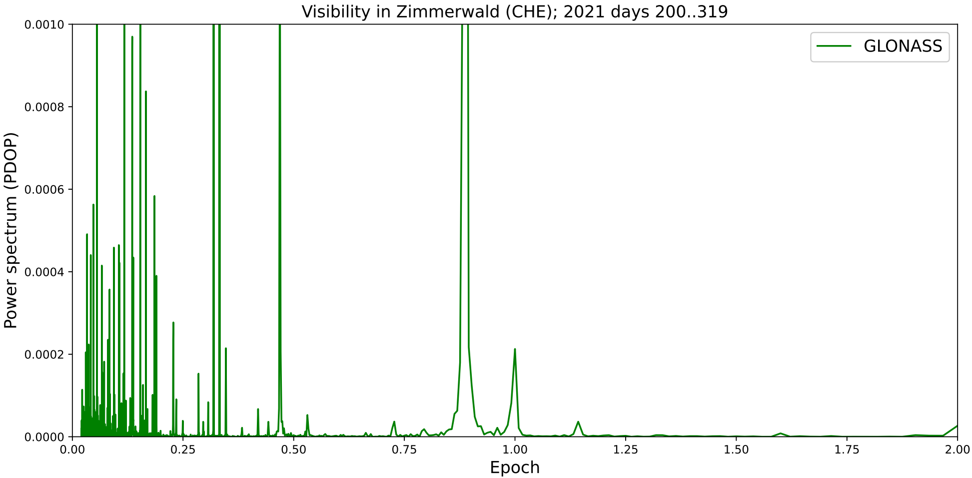

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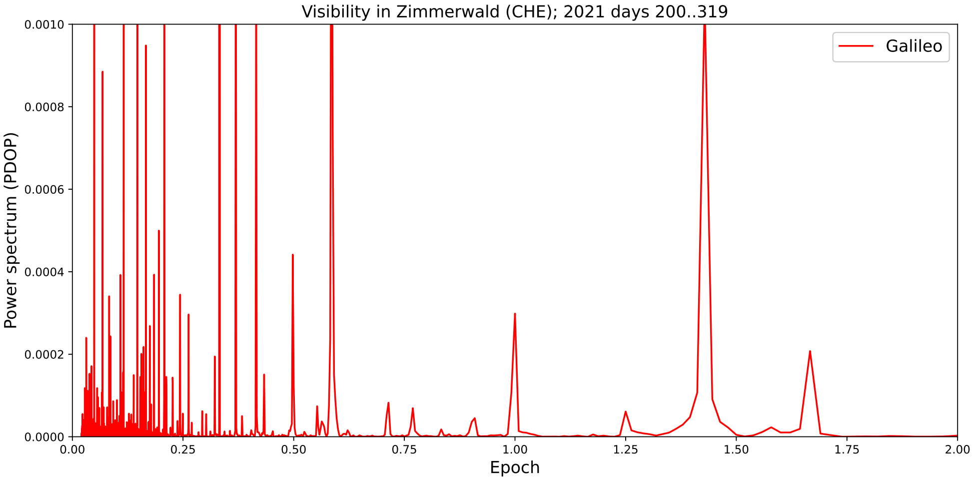

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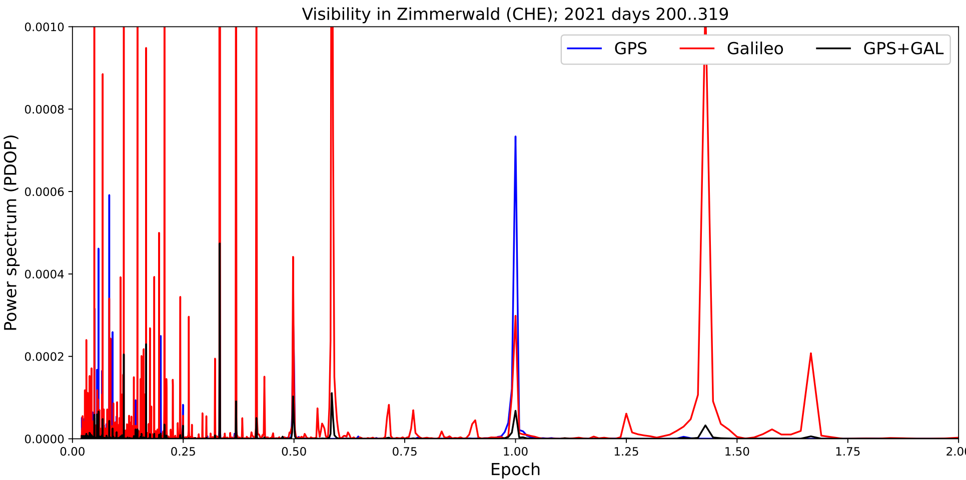

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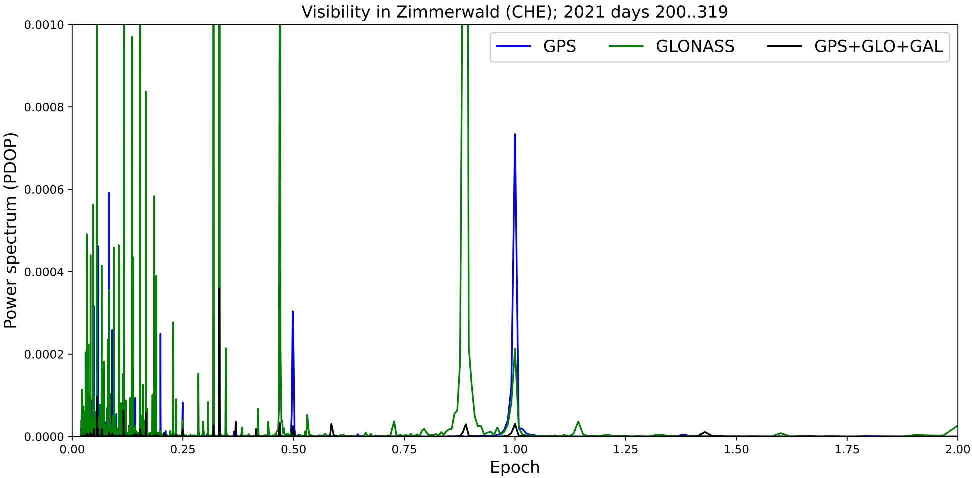
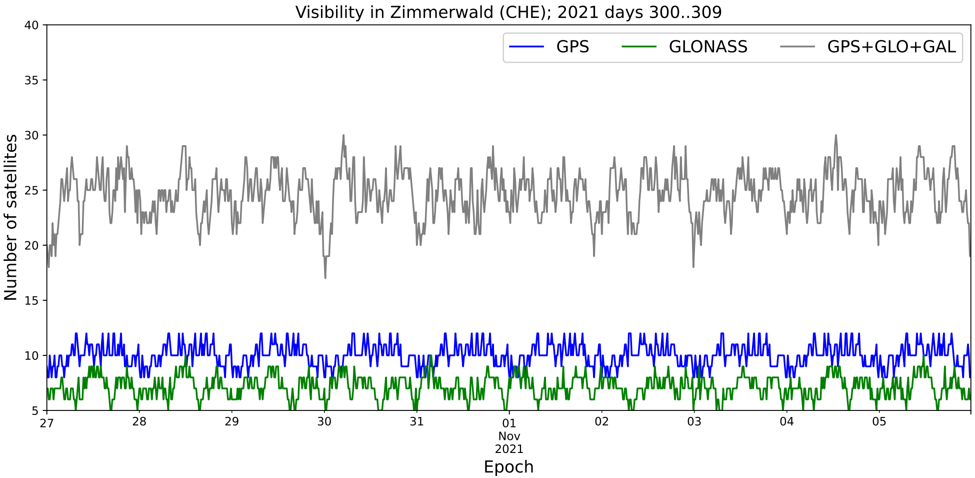


Number of visible satellites



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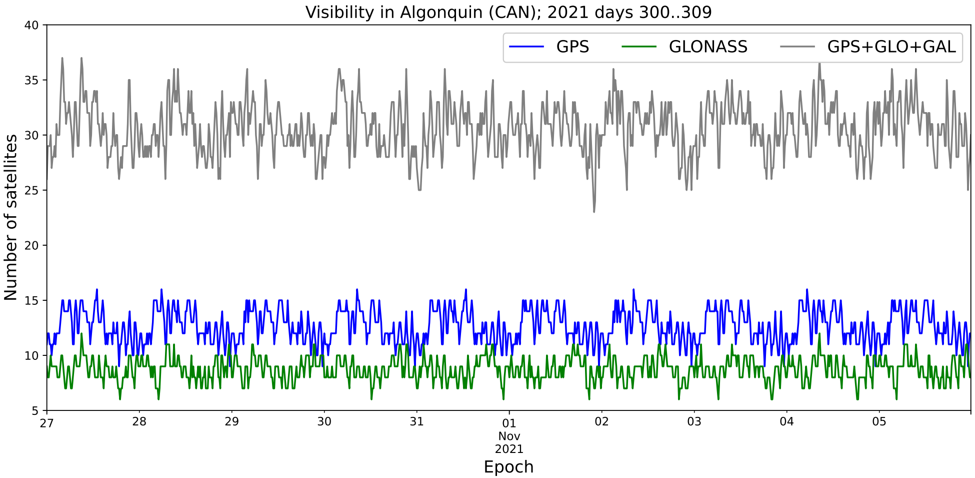

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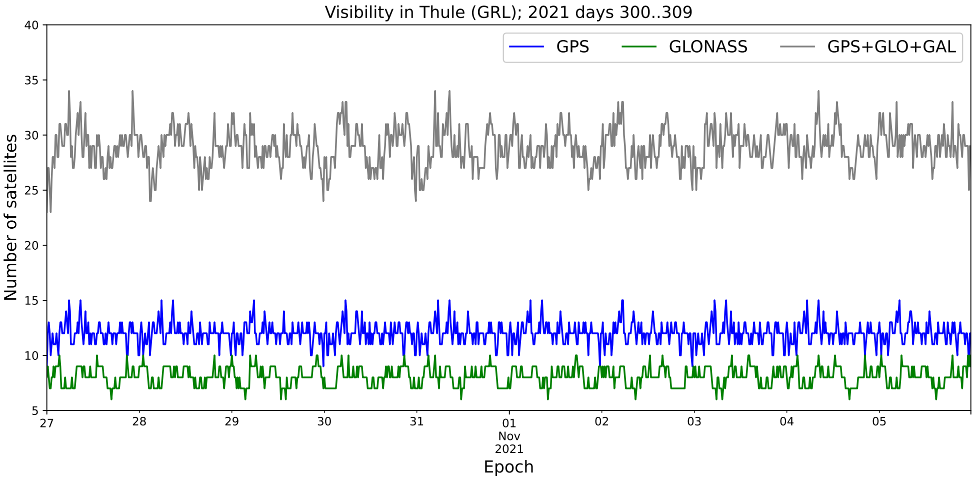
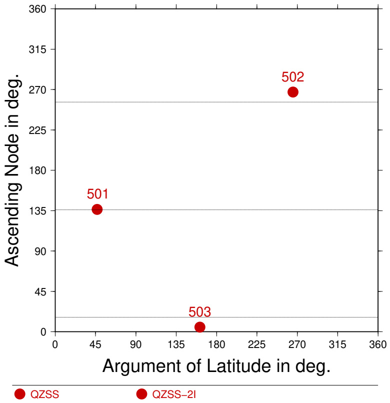


QZSS constellation

Constellation in numbers

Orbit elements for QZSS satellites

a: 42 000 km
e: 0.075
ω: 270°
i: 43°



Constellation in numbers

Orbit elements for QZSS satellites

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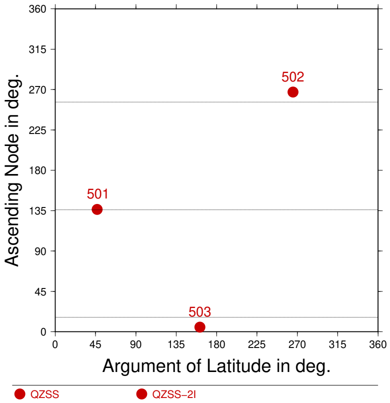
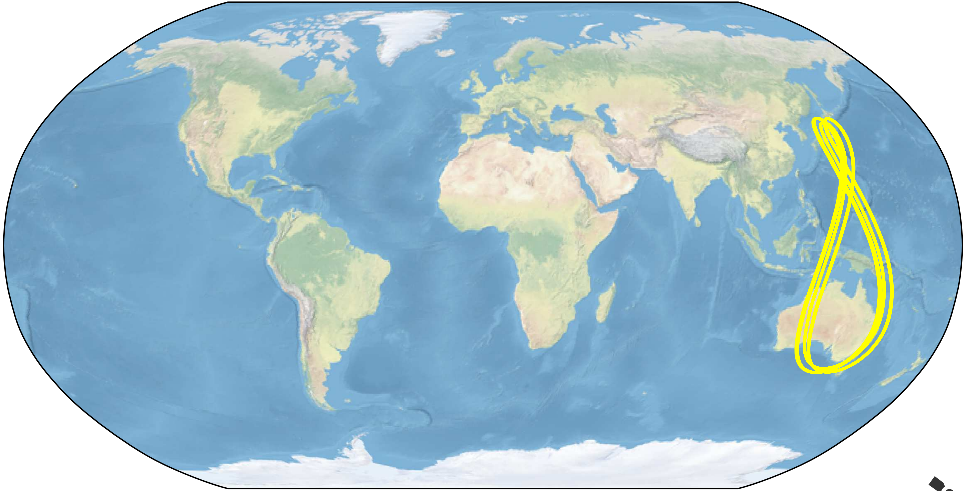


Repetition rates

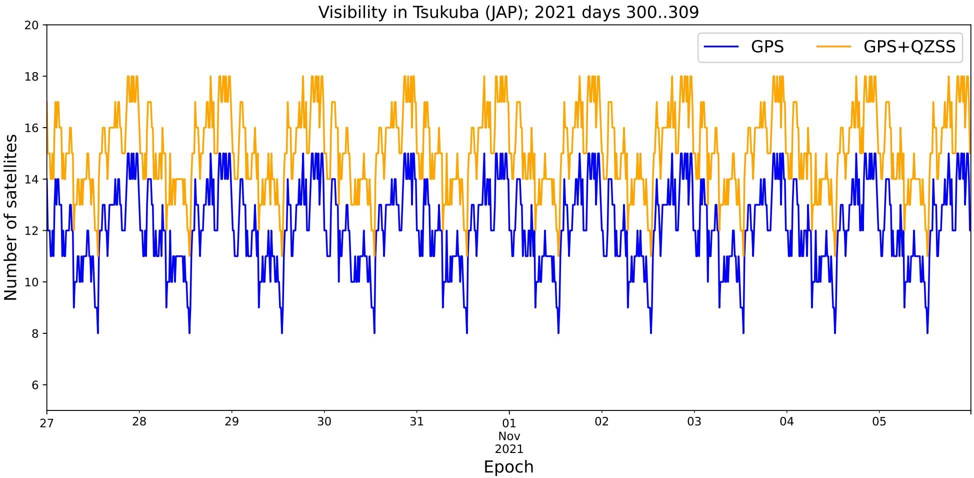
revolution period	23 h 56 min
constellation	1 sidereal day
geometry	1 sidereal day

QZSS constellation

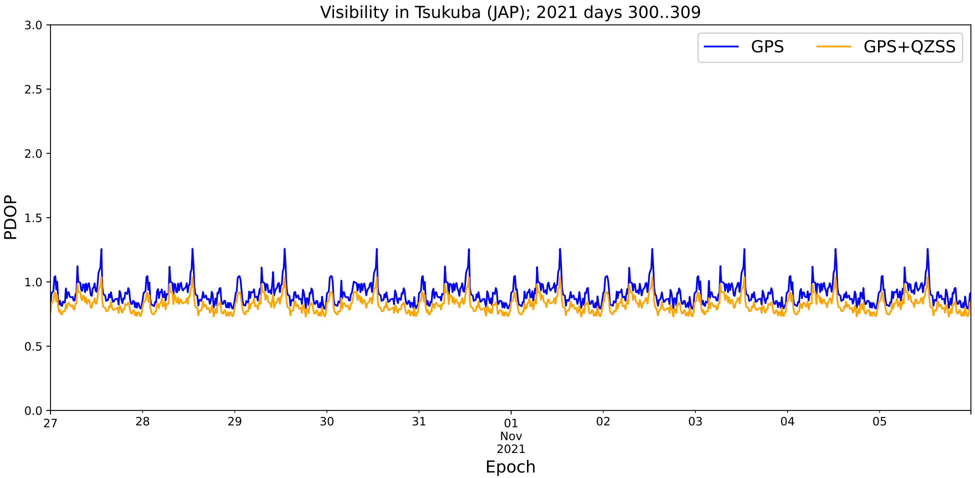
QZSS ground track, constellation, 10 days (2021, day 300..309)



Adding a regional constellation



Adding a regional constellation



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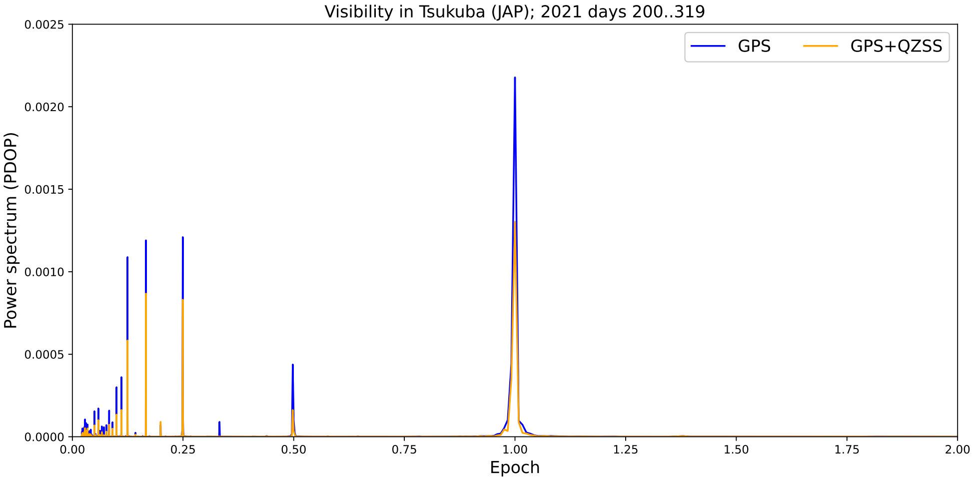

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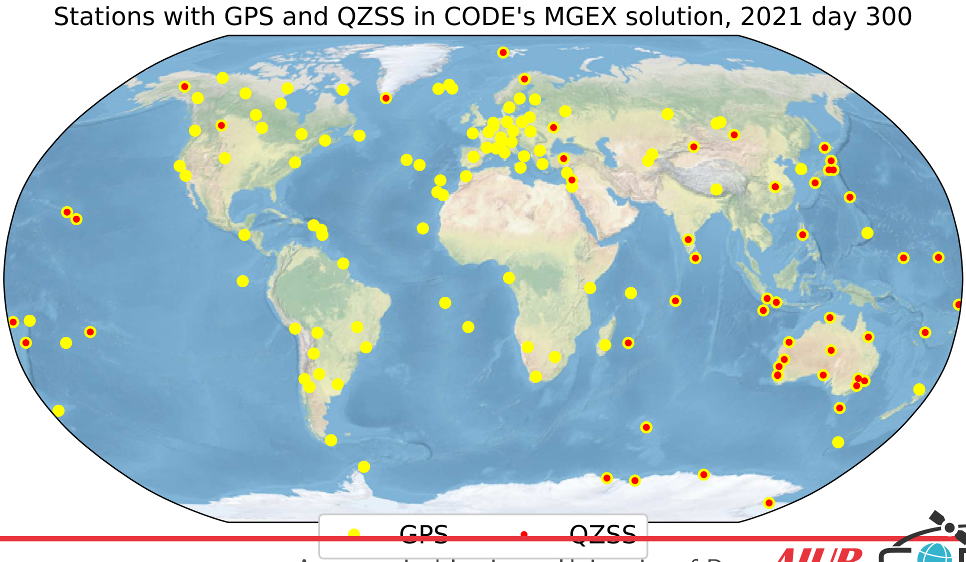

Frequency propagation

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Effects of unmodelled tidal displacements in GPS and GLONASS coordinate time-series

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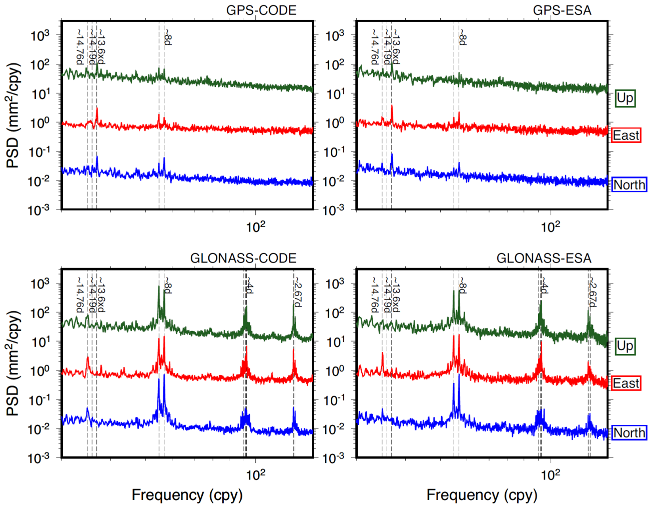

Figure 3 Stacked and normalized power spectra of GPS (upper panel) and GLONASS (lower panel) PPP solutions from both CODE (left panel) and ESA (right panel) products for stations in Fig. 2. The vertical dashed lines show fortnightly (14.76-, 14.19- and 13.6*x*-d periodic signals) and the GLONASS-specific 8-d periodic signal and its second and third harmonics (4- and 2.67-d periodic signals). The spectra are computed for north, east and up components (see colour codes) and the high-frequency section is plotted with a shift along the vertical axis for clarity.

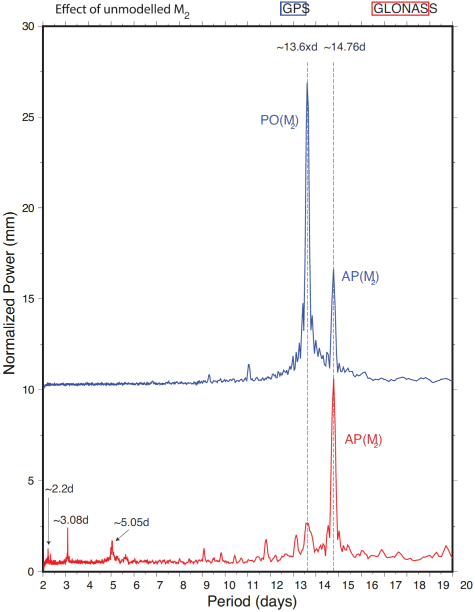

Figure 5 Effects of unmodelled M_2 OTL constituent on the (up) coordinate component for GPS (blue line) and GLONASS (red line) solutions. The normalized powers versus periods (days) are plotted with a shift along the vertical axis for clarity. The vertical dashed lines show the 13.6x-d and 14.76-d periodic signal.

Frequency propagation

Table 1. Predicted periods (in days) from propagations of unmodelled M_2/O_1 using eqs (30)–(33) of Stewart *et al.* (2005) and eq. (1) of Penna & Stewart (2003) for GPS, GLONASS and Galileo. Only the 1st to 5th terms are presented in this table. Note that an average of constantly repeating satellite geometry at sidereal day (23.934471 hr) for GPS, eight sidereal days (191.475775 hr) for GLONASS and ten sidereal days (239.344719 hr) for Galileo are adopted and used in eqs (30)–(33) of Stewart *et al.* (2005).

	M_2			O_1		
	GPS	GLONASS	Galileo	GPS	GLONASS	Galileo
1st	14.765	14.765	14.765	14.192	14.192	14.192
2nd	13.661	3.141	3.728	13.168	3.114	3.690
3rd	16.064	5.466	7.529	15.387	5.549	7.687
4th	14.192	5.180	5.952	13.661	5.107	5.857
5th	15.387	17.356	30.724	14.765	18.222	33.546

Effect of unmodelled M_2

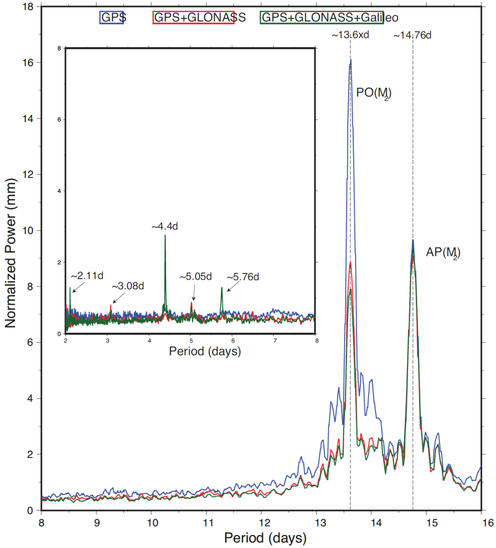

Figure 8 Effect of unmodelled M_2 OTL constituent on the (up) coordinate component for GPS, combined GPS+GLONASS and combined GPS+GLONASS+Galileo solutions. Vertical dashed lines are as in Fig. 5. The inset shows 2–8 d (period).

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